# RLSO 2

## Robotic Lunar Surface Operations 2

2019

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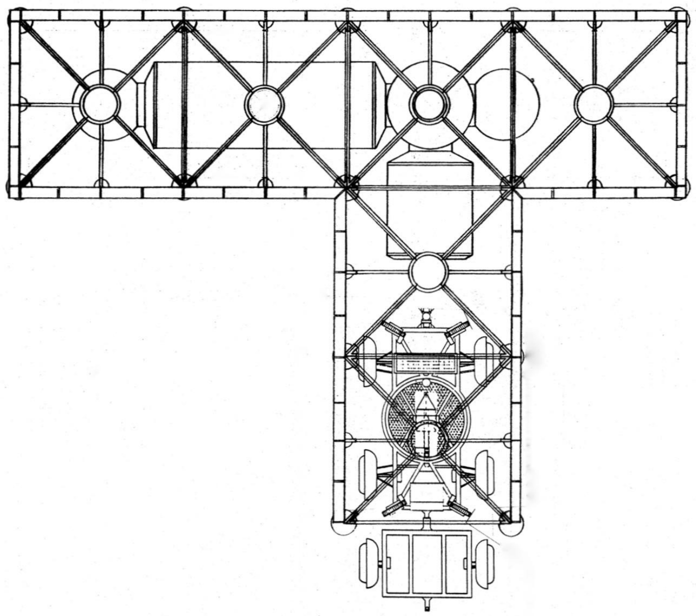
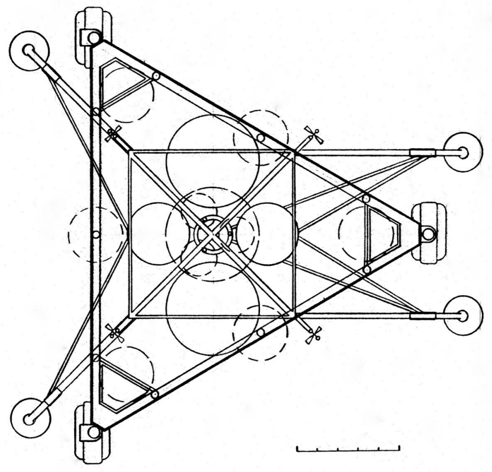
# RLSO – 1989 Boeing study for NASA ARC

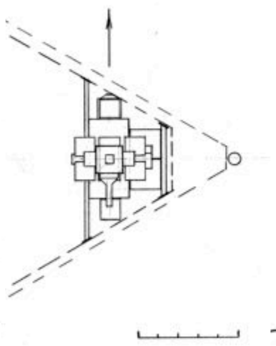
"Develop a concept for a LLOX-producing lunar base that would be built by robots before human crews arrive"

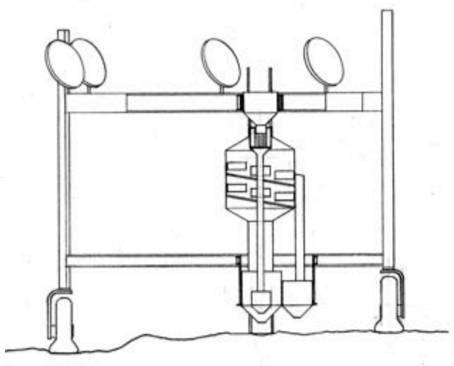
# Integrated element designs.

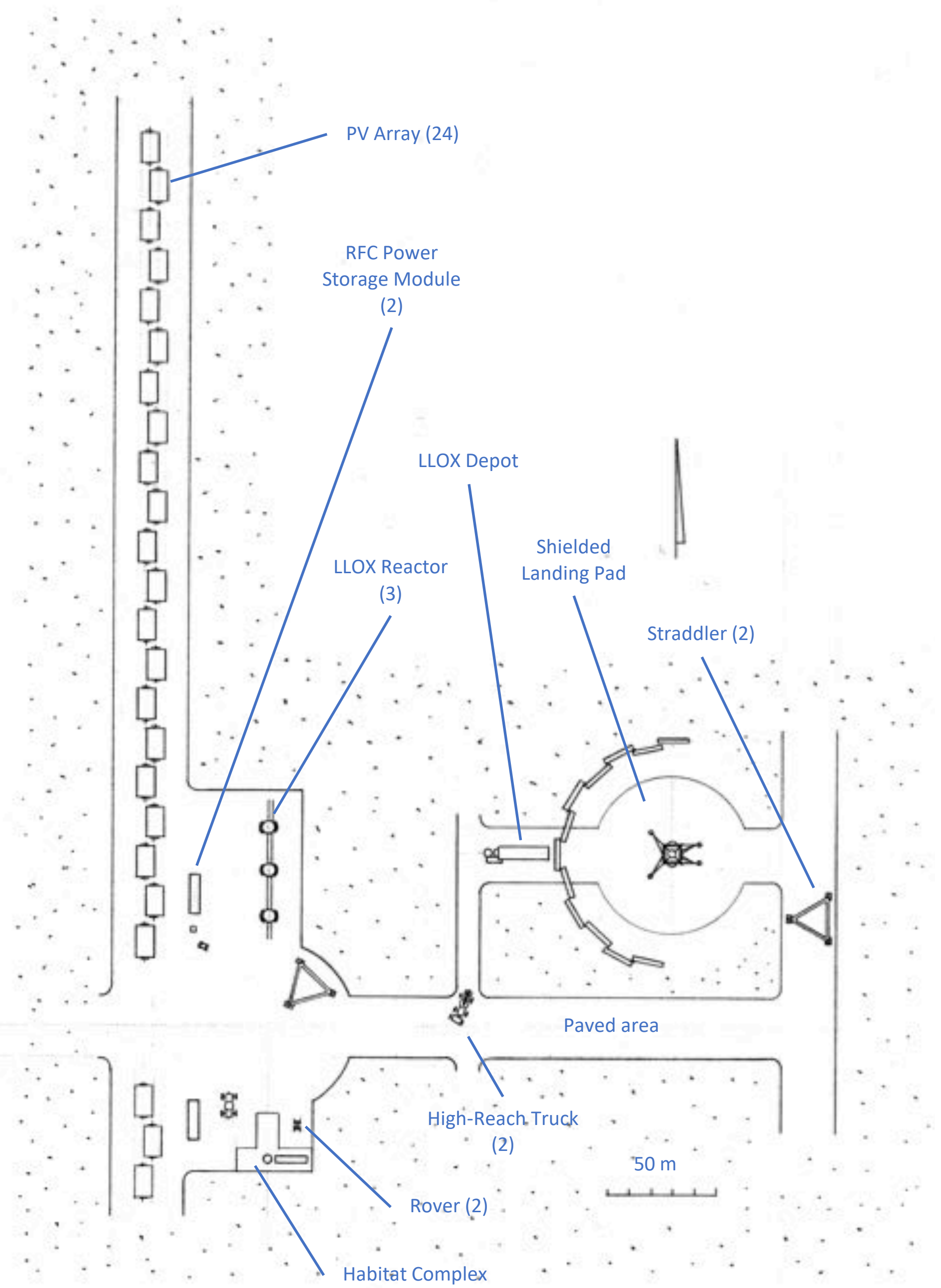
# Quantified operations analysis.







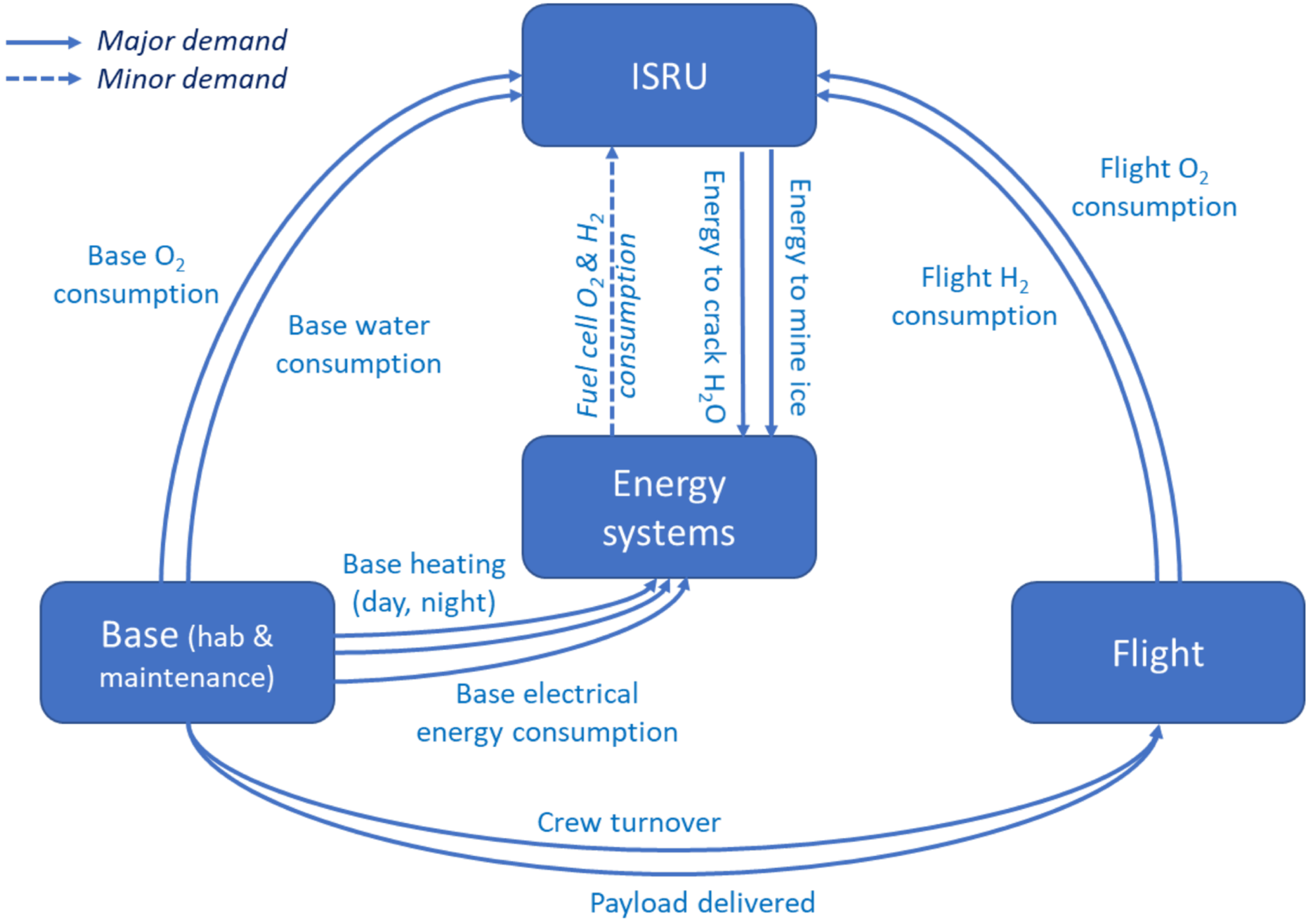




# What would RLSO look like in 2019?

- Lunar polar volatiles, including ice
- ISS experience, international collaboration
- SPD-1, Moon Village, commercial actors, private capital
- SLS, Orion, Gateway, CLPS, Blue Moon
- Modern tools: spreadsheets, CAD, performance models

# The importance of quantitative operations modeling

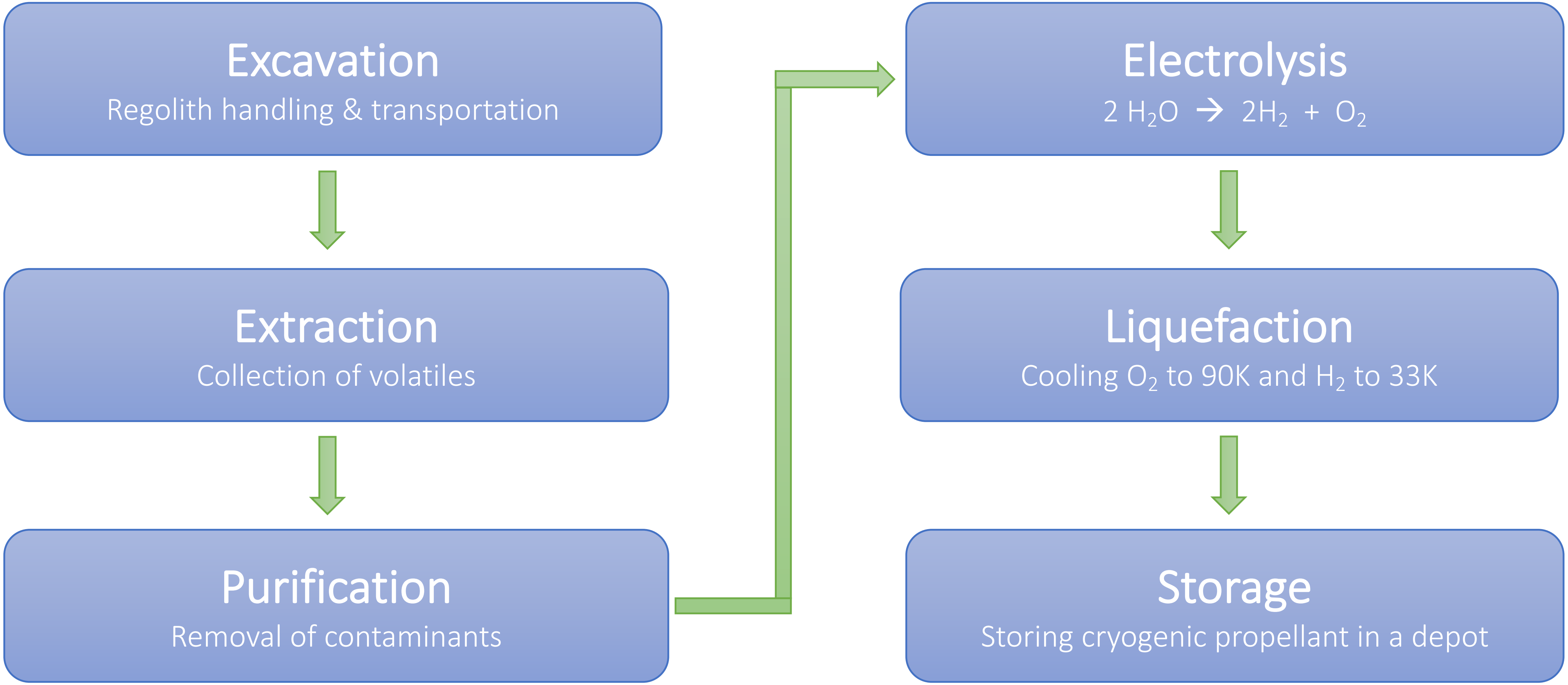



Each major element of the ops model is **flexible** and **expandable**, allowing for the integration of a wide variety of base element designs

- ISRU techniques and elements
- Energy system architectures
- Lunar lander designs
- etc.

The integrated model seeks to gracefully handle the **interconnected aspects** of the lunar base in order **to size the entire base system**

# Functional decomposition of ice-based propellant ISRU



# Major elements of an ISRU base

**Energy System** – >500 kW capacity, near-100% duty cycle, modular units landed intact, then connected via cables or laser

**Habitat System** – 30-day visits: hab, logistics, workshop, EVA, regolith-shield superstructure

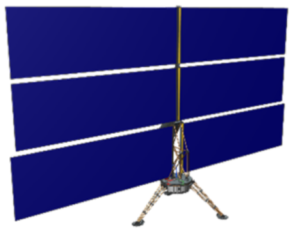
**ISRU Mining System** – Mobile robots that reach, excavate, beneficiate, and transport lunar regolith (or extract resource onboard and transport it)

**ISRU Extraction System** – Processor that separates frozen volatiles from lunar regolith

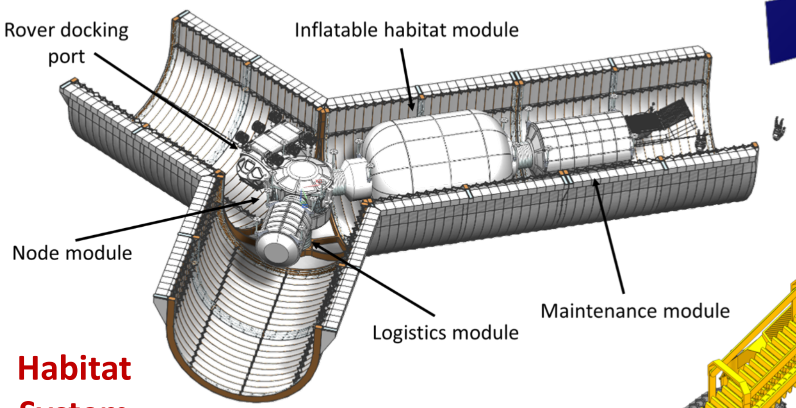
**ISRU Volatiles Processing System** – Plant that separates water from other volatiles, and cracks it into $H_2$ and $O_2$

**ISRU Depot System** – Plant that liquefies, cryogenically stores, and distributes cryogenic propellant to reusable landers

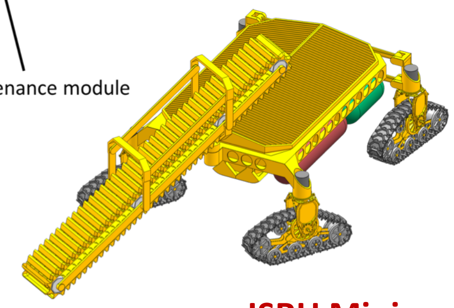
**Lander System** – Reusable, refuelable lander, reusable landing pad, and ground support systems



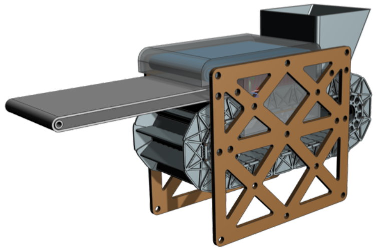
Energy System



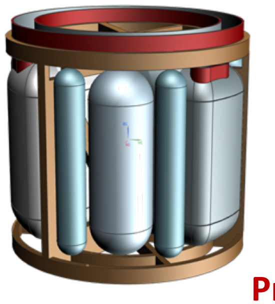

Habitat System



ISRU Mining System

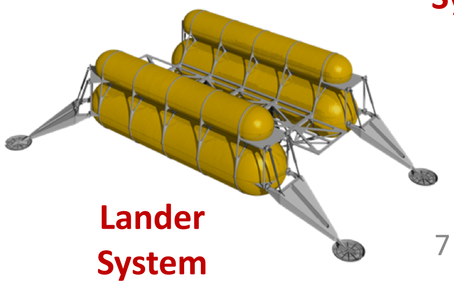


ISRU Volatile Extraction System



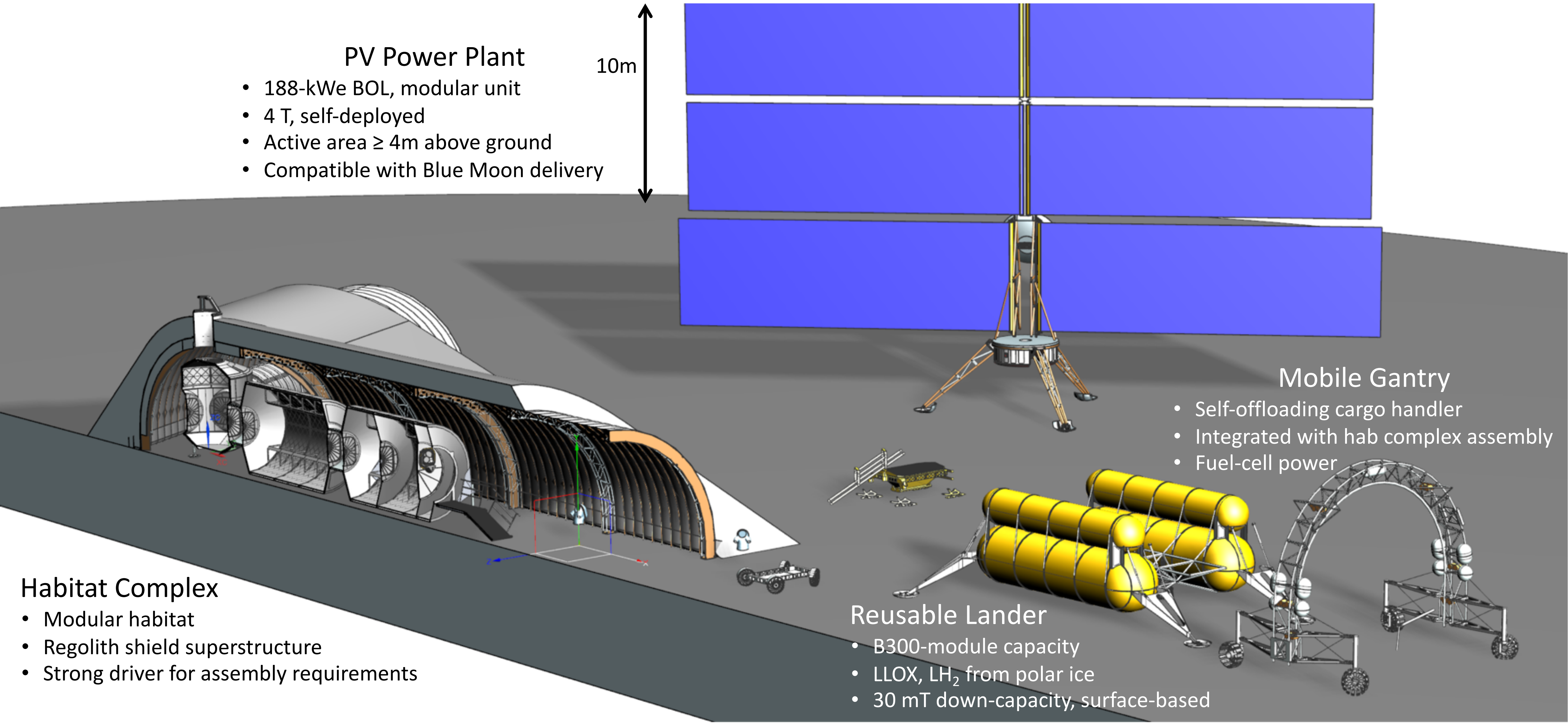
ISRU Processing System

Propellant Storage Depot



Lander System

# Base element designs must be integrated



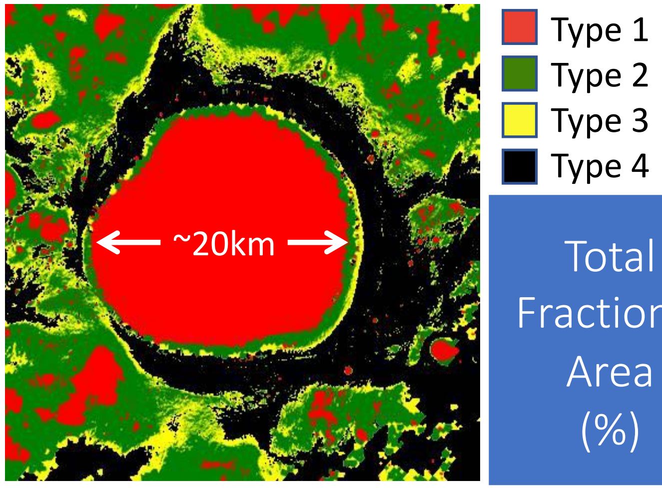

### PV Power Plant
- 188-kWe BOL, modular unit
- 4 T, self-deployed
- Active area ≥ 4m above ground
- Compatible with Blue Moon delivery

### Mobile Gantry
- Self-offloading cargo handler
- Integrated with hab complex assembly
- Fuel-cell power

### Habitat Complex
- Modular habitat
- Regolith shield superstructure
- Strong driver for assembly requirements

### Reusable Lander
- B300-module capacity
- LLOX, $LH_2$ from polar ice
- 30 mT down-capacity, surface-based

# Polar ice resources



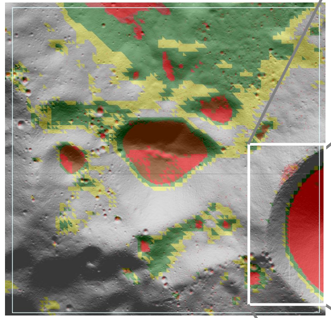

- Bin by water-stability depth into four terrain types
- Map areas that have 20-m DEM and high-res thermal models
- Illustrated: Hermite-A crater, lunar north pole

| | Total Fractional Area (%) | Water concentration (wt%) | Depth beneath the surface (cm) | Water-containing column (cm) | Total water excavated ($kg/m^3$) | Extraction area for 10 t of water ($m^2$), @30% patchy |
|---|---|---|---|---|---|---|
| **Type 1a** PSR regolith | 9 | 2 | 20-100 | 80 | 7.2 | 1,400 |
| **Type 1b** PSR surface frost | 9 | 100 | 0 - 0.002 | 0.002 | 0.006 | > 1.5M |
| **Type 2** PLR buried regolith | 28 | 1 | 40-100 | 60 | 2.7 | 3,700 |
| **Type 3** PLR deeper regolith | 7 | 0.5 | 60-100 | 40 | 0.9 | 12,000 |
| **Type 4** Lunation-lit regolith | 56 | 0 | -- | 0 | 0 | n/a |

# Option 1 – Deep Shackleton, PSR

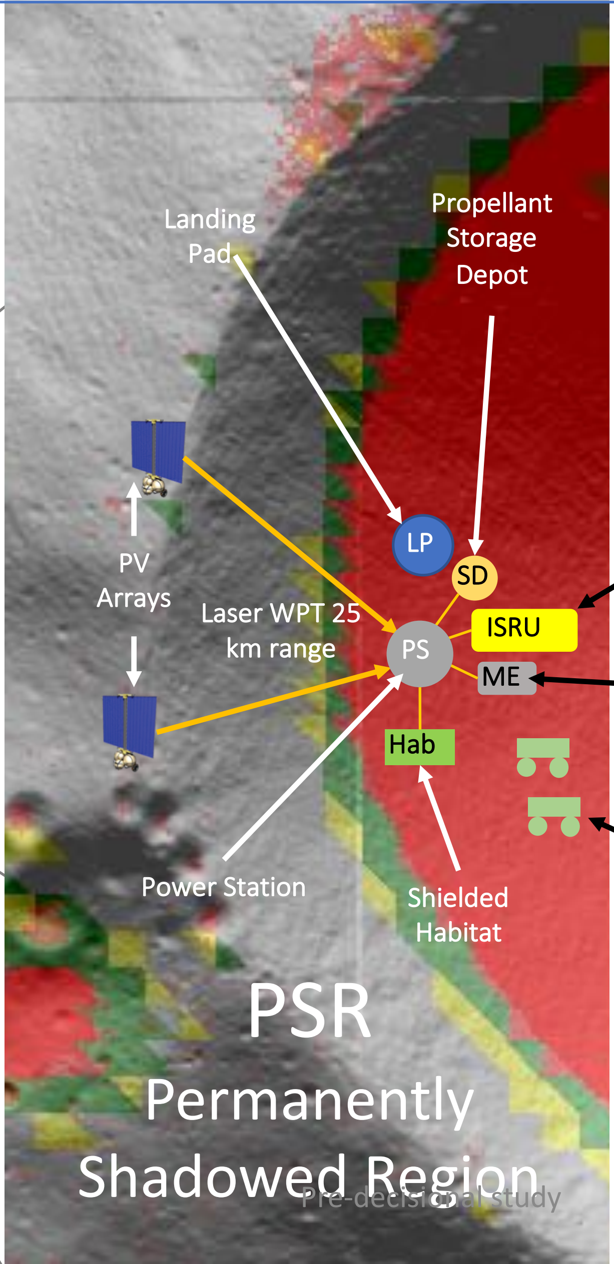
## Type 1a Resource

2 wt% water ice, found
20 – 100 cm down



## Power Infrastructure

- Multiple PV rim stations yield high lunation duty cycle
- Laser WPT to central power station
- Cable distribution to base elements
- Mobile elements use fuel cells, recharge at central station




Reach, remove, and haul regolith resource <1 km to ISRU base

## ISRU Plant

Purification
Electrolysis
Liquefaction

Central Microwave Extractor

Fuel Celled Dig/Haul Robots

**Excavation**
Dig & Haul robots

**Extraction**
Central microwave unit

**Purification**
Processing plant

**Electrolysis**
PEM or SOXE

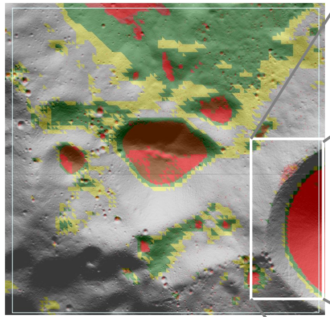
**Liquefaction**
Turbopumps & Coolers

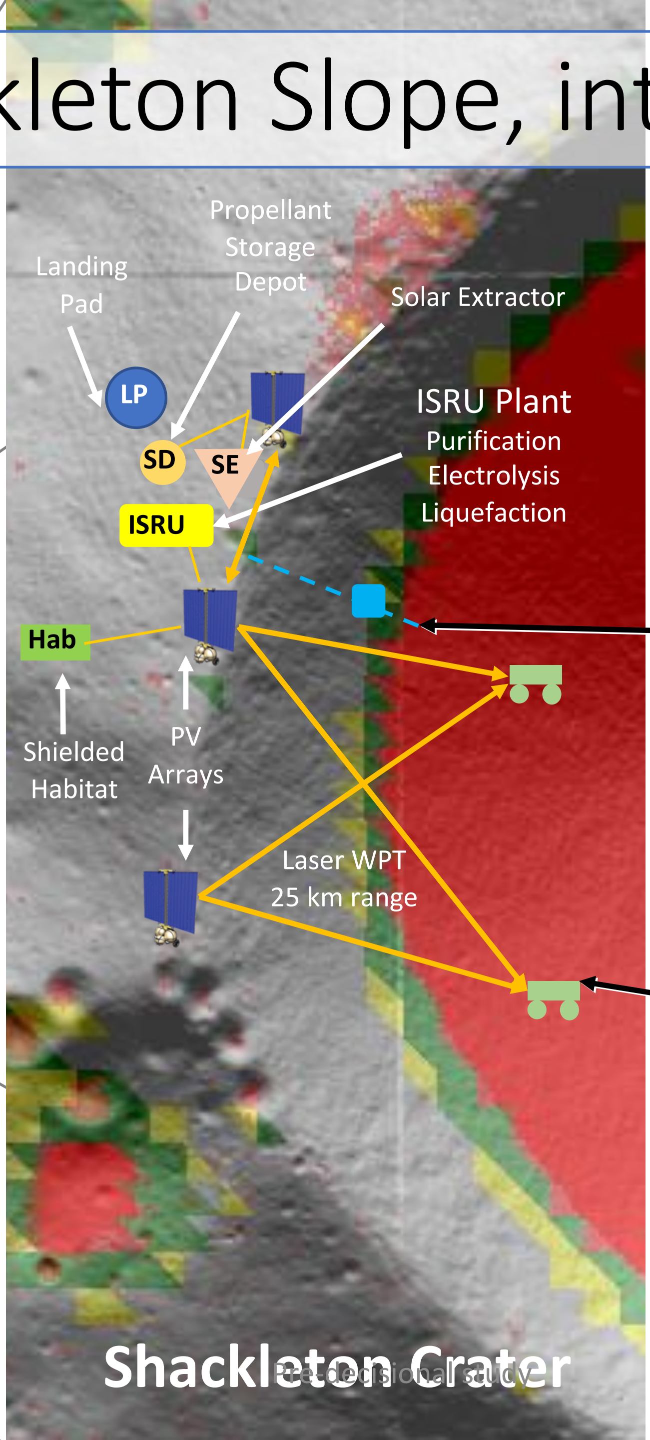
**Storage**
Depot at landing pad

# Option 2 – Shackleton Slope, into the PSR

**Type 1a resource**

2 wt% water ice, found 20 – 100 cm down






Resource "escalator"

Beam-powered Roving Beneficiators

Haul beneficiated resource <10 km up and out of the crater

**Excavation**
Roving beneficiator
Pneumatic collection

**Extraction**
Solar baking

**Purification**
Processing plant

**Electrolysis**
PEM or SOXE

**Liquefaction**
Turbopumps & Coolers

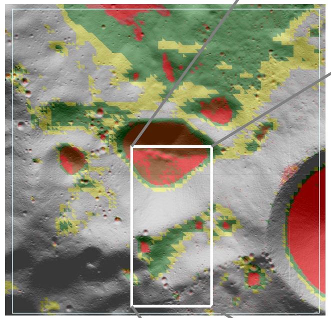
**Storage**
Depot at landing pad

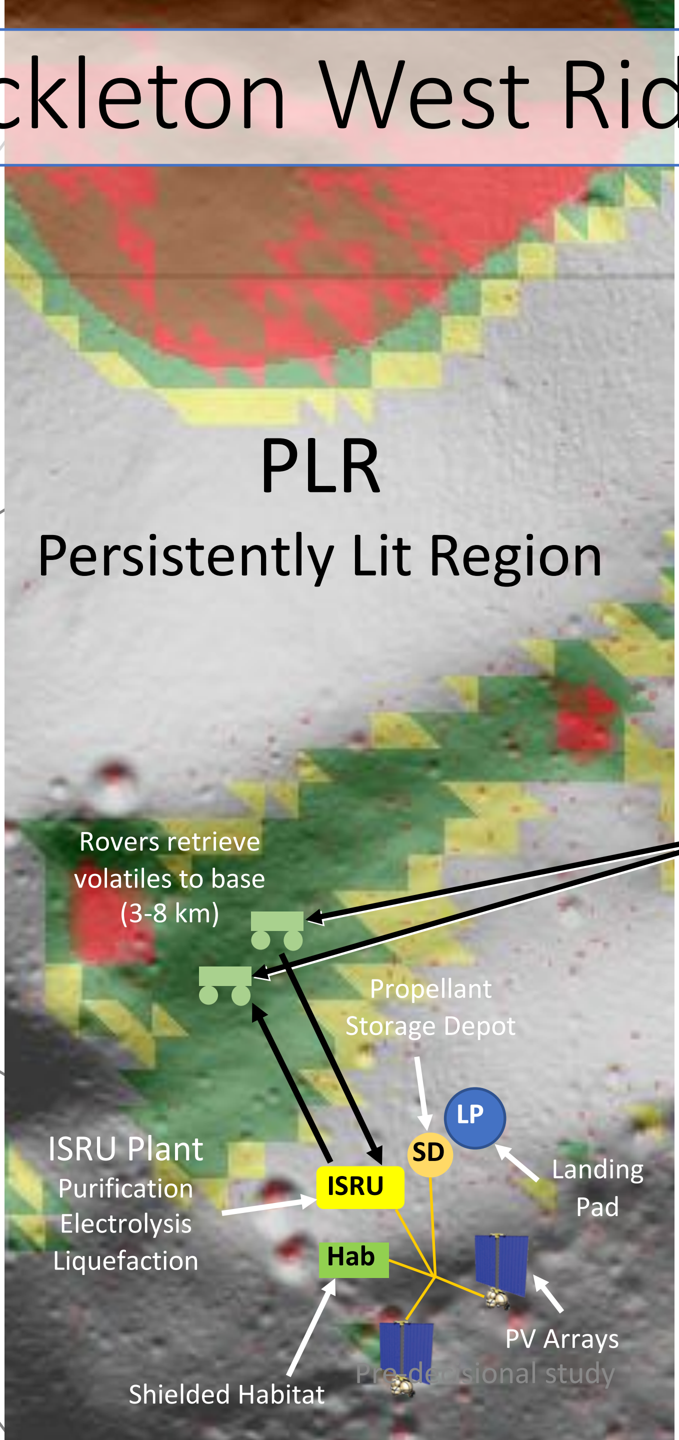
## Power Infrastructure

- Multiple PV rim stations yield high lunation duty cycle
- Power cables to base elements
- Laser WPT to excavators inside PSR
- Fuel-celled base robots

# Option 3 – Shackleton West Ridge, PLR Ice Fields

**Type 2 resource**
1 wt% water ice, found
40 – 100 cm down






## Power Infrastructure

- Multiple PV stations yield high lunation duty cycle
- Solar/fuel cell mobility
- Excavator Extractor Retriever and base robots

Transport frozen volatiles to base (3-8 km)

**Excavation + Extraction**
In situ extraction by coring rover

**Purification**
Processing plant

**Electrolysis**
PEM or SOXE

**Liquefaction**
Turbopumps & Coolers

**Storage**
Depot at landing pad

## Fleet of resource rovers

- Core into the buried resource
- Heat the cores in situ
- Freeze the volatiles
- Return to base

# Initial ISRU Requirements

## Water need

- Lander flights per year: 4
- Propellant required per flight: 40,000 kg
- Water required per flight: **51,500 kg** (6:1 engine ratio vs. 8:1 water mass ratio)
- Water need: 206,000 kg/yr = **1,130 kg/d** @ half-time operations

## Resource assumptions

- Type 1: **0.15 m$^3$ (~210 kg) regolith** per kg of $H_2O$ yield
- Type 2: **0.40 m$^3$ (~600 kg) regolith** per kg of $H_2O$ yield

## Regolith need

- Type 1: 240,000 kg/d @ half-time
- Type 2: 680,000 kg/d @ half-time

# Base Energy Requirements

Volatiles processing minimum: **10.5 kWh per 1 kg of water**

- 2 kWh/kg for extraction from regolith
- 6.5 kWh/kg for electrolysis: $H_2O$ into $H_2$ and $O_2$
- 2 kWh/kg for liquefaction: $H_2$ and $O_2$ into $LH_2$ and LOX

ISRU energy: **2,200,000 kWh/yr**

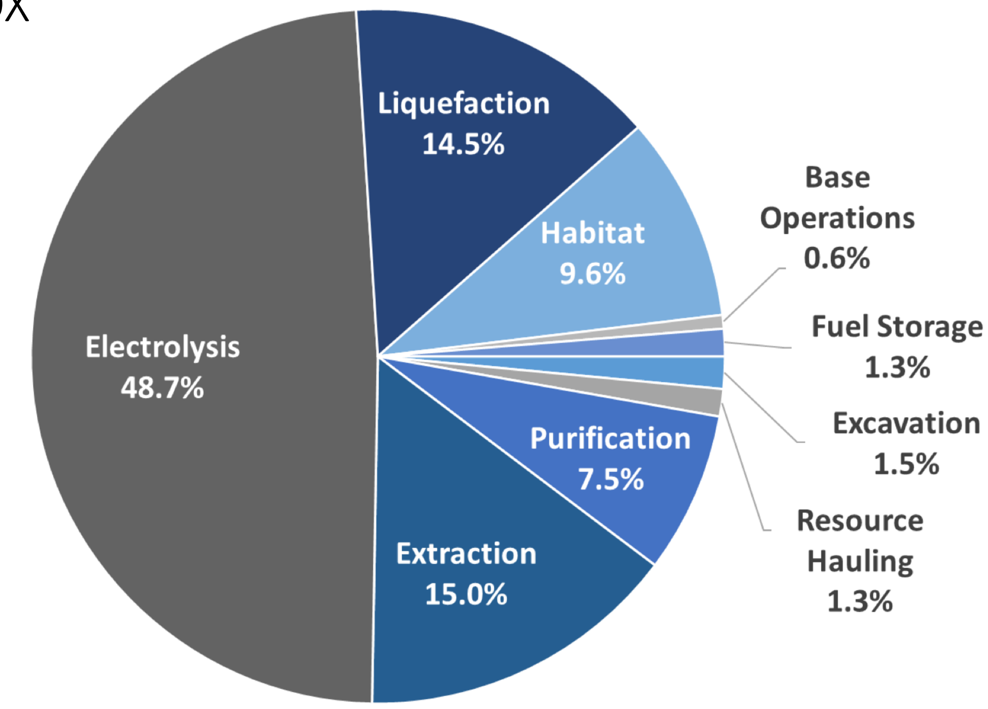
- Quantity of water required: 206,000 kg/yr

ISRU power: **500** kW @ half-time ops (4,380 hr)

Other energy requirements include:

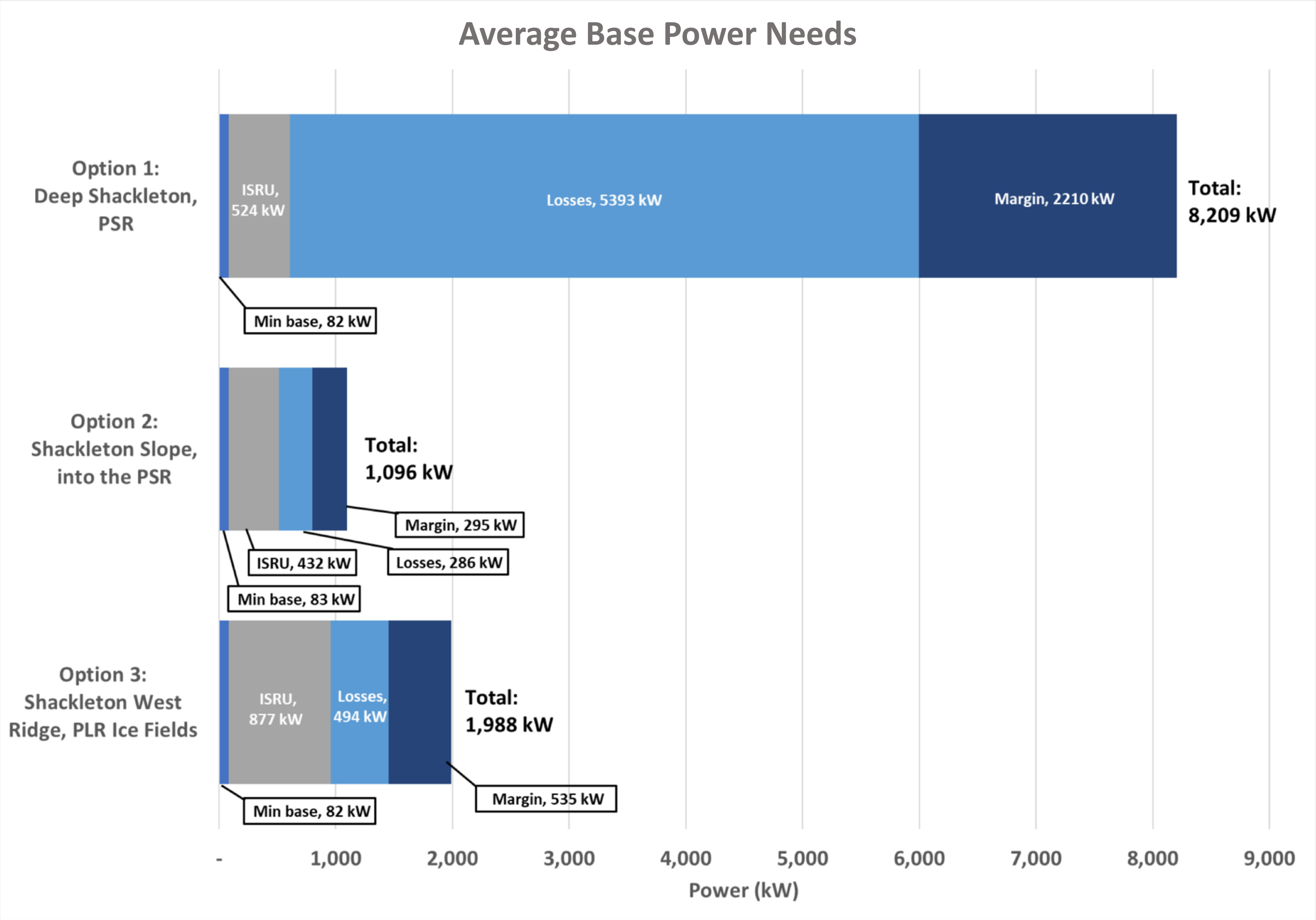
- Excavation, hauling, cryogenic storage
- Hab-complex sustained operation
- General mobility and base operations
- Power losses (cables and beaming)

Total base power need: ≥600 kW



# Comparing energy needs across base options

- Minimum base (habitat + flight) power need is approximately the same for each architecture
- ISRU dominates power need over minimum base
- Cable and beaming losses are a substantial fraction of the power budget in all cases
- Scheme 1 suffers significantly higher losses because the energy-expensive processing is a long way from the power source



# Option comparison

| Option | Best attributes | Worst attributes |
|---|---|---|
| 1.<br>Deep Shackleton | • Best quality resource, with minimal overburden removal<br>• Stable operating environment: dark, 70K | • Significant power distribution losses<br>• **Base cannot easily access regional exploration sites**<br>• **Base is permanently dark** |
| 2.<br>Shackleton Slope | • Best quality resource, with minimal overburden removal<br>• **Base can support exploration excursions** | Resource must be brought several km up and out of crater |
| 3.<br>Shackleton West Ridge | • Avoids crater slopes<br>• Proximate sunlight and shadow<br>• 0.5m/px LROC imagery<br>• **Base can support exploration excursions** | “Half-quality” resource, buried deeper |

# Emergent findings

"Best" ice resource and location may not be in a PSR

Nuclear power useful for production-scale ISRU would have to be MWe class

Potential competitive roles for commercial actors

- Power providers, extraction rovers

Empirical knowledge gaps with high leverage

- Vertical distribution at m scale – wt% of ice as a function of depth
- Horizontal distribution at km scale – patchiness of resource "field"
- Geotechnical properties – "coffee grounds and sugar" or cryo-permafrost
- Diffusion rate – trapping vs losing the resource from heating in situ
- Agitation loss coefficient – losing the resource from handling it

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